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^{163}Dy AS A SOLAR NEUTRINO DETECTOR

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^{163}Dy as a Solar Neutrino Detector *

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ABSTRACT

The possibility of using ^{163}Dy as a low threshold solar neutrino detector is discussed. Solar neutrino absorption cross sections are calculated, and expected capture rates presented.

INTRODUCTION

Perhaps the most favorable reaction with respect to nuclear structure for detecting low energy neutrinos is ^{163}Dy(ν_e,e)^{163}Ho. The reason for considering ^{163}Dy in particular, is that it has the lowest threshold for neutrino reactions of all stable isotopes. Unfortunately, it is probably the most difficult reaction with respect to the chemical separation required. Since some of the relevant nuclear properties for this transition have recently been precisely measured by our group in connection with a search for neutrino mass effects[1] in the decay of ^{163}Ho, it is worthwhile to consider whether using ^{163}Dy as a solar neutrino detector might be of interest.

The nuclear structure of the ^{163}Dy to ^{163}Ho transition is quite favorable. The ground state of ^{163}Dy is the lowest member of a neutron $5/2^-$[523] rotational band, while the ^{163}Ho ground state is the lowest member of a proton $7/2^-$[523] rotational band. Thus the two ground states differ essentially only by a different coupling of the odd particle's spin to the same underlying intrinsic state, and the fact that the odd particle is a proton in the one case, and a neutron in the other. As a result, the electron capture is a so called allowed unhindered transition, and the nuclear matrix elements are large. None of the excited states in the ^{163}Ho ground state band can be connected with an allowed matrix element, since their spins are all greater than 7/2. The lowest excited state beyond the ground state which can be reached by an allowed transition is the $5/2^-$ state at 527 keV excitation. This state is beyond reach of the pp neutrinos, and has a negligible cross section for pep neutrinos on a kinematic basis alone. Furthermore, since this state is not a member of the ground state $7/2^-$[523] rotational band, the intrinsic cross section for neutrino capture from the target ^{163}Dy $5/2^-$[523] state will be negligible. The same effects will apply to any of the higher excited states as well, since there is only one allowed unhindered state in ^{163}Ho which can be reached by solar neutrinos, and that is the ground state itself.

MEASUREMENTS

The two recent measurements which are relevant for estimating the solar neutrino cross section are the total half-life[2]

$$T_{1/2}=4570+/-50 \text{ years (90\% confidence level)} \tag{1}$$

and the ratio of the N capture rate to the M capture rate[3]

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$$\lambda_N/\lambda_M = 3.82+/-0.4 \tag{2}$$

These two measurements can be combined to yield the electron capture Q_{EC} value and the nuclear matrix element,

$$Q_{EC} = 2564+/-50 \text{ eV} \tag{3}$$

$$ft_{1/2}=79{,}900\text{sec} \tag{4}$$

The various factors which enter in determining (3) and (4) are given in table I. The notation used is that of ref. 4. It is interesting to note that the ft value of 86,600 for ^{161}Ho is very similar to the value of 79,900 for ^{163}Ho.

One of the uncertainties in deriving the Q_{EC} and ft values from the experimental measurements is the absence of a calculation of the overlap and exchange correction factors for some of the outer shell orbits in dysprosium. The values assumed in deriving (3) and (4) listed in table I are based on interpolation and extrapolation of values from ref. 4. In particular, for the most important unknown overlap and exchange factors, i.e. those for the $3p_{1/2}$ and $4p_{1/2}$ orbitals, it was assumed that the average of the 3s and $3p_{1/2}$ factors was 1.0, and the average 4s and $4p_{1/2}$ factor was also unity. This assumption leaves much to be desired, but is probably better than using equal factors for 3s and $3p_{1/2}$. In any case, the uncertainty introduced in the total phase space factor for electron capture in ^{163}Ho is only at the level of 1%.

The cross section for neutrino capture in ^{163}Dy is given by[5]

$$\sigma(\nu_e,e)=2.629\times10^{-41}\text{cm}^2 p_e W_e F_0 L_0 C(W_e)_\nu/(ftC(W_e)_e \tag{5}$$

where p_e and W_e are the emerging electron's momentum and energy in atomic units, and F_0L_0 is the Fermi function for the ^{163}Ho + $_e$ reaction products.

Using our measured ft value, and correcting for the spin statistics factors the neutrino capture cross section becomes

$$\sigma(\nu_e,e)=4.4\times10^{-46}\text{cm}^2 p_e W_e F_0 L_0 \tag{6}$$

With these expressions, approximate average cross sections for some of the more important neutrino sources in the sun have been calculated, and are listed in table II. For the standard solar model, the capture rate in ^{163}Dy is about 850 SNU's. This is larger than for any of the isotopes so far considered. The amount of ^{163}Dy needed for one capture per day is about 3.7 Tons. In the form of $DyCl_3$, the amount needed for one capture per day is 25 Tons, or 6.7 m^3.

The equilibrium concentration of ^{163}Ho in natural $DyCl_3$ from the solar neutrino flux alone would be about 0.36 atoms per cm^3. However, since holmium and dysprosium will inevitably be present together geologically, the (p,n) reaction on ^{163}Dy would produce a far larger abundance of ^{163}Ho than the solar neutrinos, and since the actinides are likely to be associated with the lanthanides, there would be no shortage of low energy protons. This fact eliminates the possibility of using ^{163}Dy in a geochemical type of experiment.

Finally, with regard to the separation of a few atoms of ^{163}Ho from 25 tons of dysprosium chloride: This is not easy. Although the amount of dysprosium needed is not in excess of the annual production by the rare earth industry, it is a significant fraction. At this stage it is too early to say much about the feasibility of extracting the neutrino generated ^{163}Ho. Suffice it to say that it does not appear totally absurd. It is worthwhile pointing out that in the final detection stage, the resonance ionization schemes being applied to the detection of ^{81}Kr in the ^{81}Br based experimental proposal are far more readily applied to the detection of ^{163}Ho, in fact the first pure rare earth compound laser was based on HoF_3. This could be a great advantage since such a laser would be intrinsically resonant with a holmium atomic transition.

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Table I

Phase Space Factors for $^{163}Ho(7/2^-[523]) \rightarrow ^{163}Dy(5/2^-[523])$, Q_{EC}=2564eV

Shell x	Energy	$q_x^2 \cdot 10^6$	$\beta_x^2 \cdot 10^3$	B_x	$f_x \cdot 10^9$
$3s_{1/2}$	2029.3	1.10	49.52	1.065	0.909
$3p_{1/2}$	1824.2	2.10	2.605	0.935	0.080
$4s_{1/2}$	406.7	17.83	11.54	1.12	3.620
$4p_{1/2}$	322.6	19.25	0.589	0.88	0.157
$5s_{1/2}$	68.7	23.86	1.71	1.18	0.756
$5p_{1/2}$	33.9	24.53	0.07	0.82	0.022
					Total=5.54

Table I

Solar Neutrino Capture Rates in ^{163}Dy

Source	Cross Sect	Flux($cm^{-2}s^{-1}$)	Rate(SNU)
$p+p \rightarrow d+e^+ +\nu_e$	$1.2 \cdot 10^{-44}$	$6.1 \cdot 10^{10}$	740
$p+e+p \rightarrow d+\nu_e$	$5.9 \cdot 10^{-44}$	$1.5 \cdot 10^{8}$	9
$e+^7Be \rightarrow ^7Li+\nu_e$	$3.0 \cdot 10^{-46}$	$3.4 \cdot 10^{9}$	100
			Total=$850 \cdot 10^{-36} s^{-1}$